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Changes in multiple ecosystem services between 2000 and 2013 and their driving factors in the Grazing Withdrawal Program, China

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ABSTRACT

Quantitative assessment of ecosystem services in the Grazing Withdrawal Program (GWP) of China is required to understand the effectiveness of environmental protection programs and the sustainability of grassland ecosystems. This study focused on quantitative assessment of changes of key ecosystem services and their driving factors in the GWP from 2000 to 2013. Based on widely used biophysical models, including the GLOPEM-CEVSA model, the precipitation storage method, Integrated Valuation of Ecosystem Services and Trade-Offs (InVEST), Revised Wind Erosion Equation (RWEQ) and Underground Productivity Model (UPM), this study integrated multi-source data to analyze dynamic changes of regulating services, including carbon sequestration, water regulation, sand fixation and soil retention, and the provisioning service of grassland yield. For the GWP area during 2000–2013, the ecosystem pattern remained relatively stable and multiple ecosystem services showed overall improvement but there were local deteriorations. For the 14 years net primary productivity (NPP) and grassland yield (GY) increased substantially. Water regulation in forest, grassland and wetland/water body ecosystems improved slightly. The soil conservation function of the entire ecosystem was slightly enhanced with soil retention showing an increasing spatial homogenization and wind erosion having a decreasing tendency. Ecological restoration and reconstruction efforts and climate change helped to improve ecosystem services. Increases in both temperature and precipitation and ecological rehabilitation had a positive effect on vegetation restoration related to a marked increase of vegetation coverage. Increase in annual precipitation increased rainfall related erosion but also assisted water regulation. Reduction in wind speed effectively lowered the occurrence of wind erosion. Vegetation restoration directly increased NPP and GY, and was conducive to water regulation and soil conservation. However, grassland degradation still continued in local areas. Ecological programs applied to the grasslands of China should be continued. Adopting adaptive management approaches that facilitate the synergy of multiple ecosystem services are required to maximize their benefit to the people of China.

1. Introduction

Natural grassland, the largest terrestrial ecosystem in China, has an area of 3.92 million km^2 occupying approximately 41.7% of the country's territory (Fan et al., 2008; Huang et al., 2016). There are three distinct and typical geographic regions in China: the temperate steppe of the northern arid region (48%), the alpine grasslands of the Tibetan plateau at very high elevations (35%), and the tropical – subtropical grassland of the southern humid region (17%) (Liao and Jia, 1996). For the Earth's largest developing country, grassland is the foundation for the rapid and healthy development of animal husbandry. Importantly, grassland also functions as the vital green ecological protective screen for China and even more extensively for Asia. Grasslands play a key role in providing a variety of ecosystem services, including livestock products, water regulation, soil conservation, carbon sequestration, and biodiversity maintenance (Chen et al., 2017; Huang et al., 2013; Yu et al., 2005). Structural and service changes of grassland ecosystems directly or indirectly affect

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the ecological and social environments essential for human survival and development.

The situation of China's current grassland ecological environment is grim. About 90% of the total grassland area of China has suffered various degrees of degradation since the 1980s. At the end of 2002, the area of deteriorated grassland had reached 135 million ha, and was still increasing at the annual rate of 2 million ha. Kawanabe et al. (1998) reported that during the past 40–50 years degraded grassland covered one-third of the area of north-eastern China and Inner Mongolia. Zhou et al. (2005), in field investigations of alpine meadows in the source region of the Yangtze and Yellow Rivers, estimated that the area had approximately 357×10^4 ha of degraded grassland, of which 21% was heavily degraded. Grasslands degradation results in serious ecosystem structure deterioration and ecosystem services recession, e.g. land desertification, lake shrinkage, wetland degradation, soil erosion, loss of carbon sinks, and more frequent occurrence of sand storms (Han et al., 2018). Degradation was primarily attributed to the integrated effects of highly intensive anthropogenic activities and accelerated climate changes (Yang et al., 2016, Liu et al., 2018). Climatic variations damaging grasslands mainly included global warming (Yu et al., 2012), changing seasonal precipitation patterns causing droughts and floods (John et al., 2013), and wind caused sand erosion (Wang et al., 2006). The negative aspects of human activities mainly include long-term overgrazing (Harris, 2010) and cropland expansion and intensive use (Ren et al., 2016). The Chinese government, as well as many environmental specialists, have generally realized the seriousness of grassland degradation in that it endangers regional ecosystem services and functions (Wang et al., 2017a,b). This degradation results in deterioration of the quality of vegetation and soils, weakening self-restoration functions, losing ecosystem services, and causing property damage (Ouyang et al., 2016).

In the face of the rapid grassland degeneration, since 2000 the Chinese government at the national scale has implemented a series of ecological programs and policy measures to reverse the degradation trend and to enhance ecosystem services. The most important of these programs are the Grain for Green Project (GGP), the Beijing-Tianjin Wind/Sand Source Control Program (BTWSSCP), the Grazing Withdrawal Program (GWP) and the Ecological Subsidy and Award System (ESAS). Of the grassland ecological rehabilitation programs, the GWP has involved the most investment, has the largest scale, has had the most remarkable effect, and has been of most benefit to Chinese herdsmen. According to the grassland survey report of Ministry of Environmental Protection of the Peoples Republic of China, by 2013 the cumulative total investment of the GWP exceeded 20 billion RMB. Particularly, by 2013 the total area of fenced grasslands had increased to 64.48 million ha. However, assessment of the effectiveness of these ecological programs have been varied and controversial. Some experts consider that the program measures have relieved grazing pressure to bring about recovery of vegetation (Bao and Zhang, 2015; Xing et al., 2005), have improved ecological conditions and have achieved the efficient and sustainable utilization (Xu et al., 2007; Zhang et al., 2016). Conversely, other experts argue that fencing natural grassland has fragmented ecosystems to increase their vulnerability to environmental change (Li and Huntsinger, 2011), long-term grazing exclusion has disturbed the original livestock-forage interaction to adversely affect rangeland quality (Gu and Li, 2013), and that the programs will ultimately result in reduction of animal husbandry and decrease the livelihood of herdsmen (Ho, 2009; Wang, 2009). These opinions are based on the dynamic monitoring of a few indicators in specific areas and mainly involved field experiments and household surveys (Gongbuzeren et al., 2015). Further, the effectiveness of these projects and information on the dynamics of China's grassland are mainly on a large scale derived from official reports and statistics. Some previous studies have used remote sensing data, but have been of short duration. Comprehensive research at the national level to analyze the long-term effectiveness of GWP and to accurately assess the multiple services of China's grassland ecosystem is lacking. How to effectively evaluate the ecological effects and incorporate ecosystem service changes into policy making and planning have become urgent problems for China to solve.

Deeper understanding of the multiple ecosystem services in the GWP is of great importance for the planning and management of grasslands. By the definition of the Millennium Ecosystem Assessment (2005), ecosystem services mean the benefits gained by humans from various ecosystems, and consist of supporting service, provisioning service, regulating service, cultural service, and their interaction. Based on an overall analysis of characteristics of grassland ecosystems for the independence and quantification among different ecosystem services, data availability, practicability of the method and spatial scale, this study focused on some key and dominant ecosystem services. As grasslands significantly influence regional and global carbon balances, carbon sequestration is the first consideration. As the study area has the headwaters of several large Asian rivers, we included water regulation in the assessment. As soil loss by wind and water erosion is also serious in the study area, we assessed the sand fixation and soil retention services of the ecosystem. And, as grassland yield relates to livestock production and the livelihood of herders, it is included. Therefore, we focused on quantifying spatial-temporal changes of regulating service (carbon sequestration, water regulation, sand fixation, soil retention) and provisioning service (grassland yield) in the GWP.

The objectives of this study are for the GWP areas during the period of 2000–2013 to (1) quantitatively examine ecosystem pattern changes; (2) accurately and quantitatively evaluate changes of multiple regulating services (carbon sequestration, water conservation, sand fixation and soil retention) and one provisioning service (grassland yield) through ecological restoration programs and climate variability; and (3) assess the effectiveness of the GWP. Findings from the study are discussed with reference to the policies and practical implications of eco-environmental changes, and also to provide a reference and guide for grassland ecological protection policy-making and planning.

2. Materials and methods

2.1. Study area

Since 2003, the GWP has covered nearly 200 counties in Inner Mongolia, Xinjiang, Qinghai, Tibet, Sichuan, Yunnan, Gansu, Ningxia Provinces and the Xinjiang Production and Construction Corp (some counties have not been considered because their implementation scopes are too small and their implementation periods too short) (Fig. 1a) (Zhang et al., 2016). The total area is 319.21 million ha, accounting for about 33% of China's territory. Due to the lack of the precise scope of the GWP implementation, we use only the demonstration counties as the study area. The area includes arid, semi-arid and alpine regions with eighteen grassland types, varying from Alpine steppe to Alpine meadow, Temperate desert, Temperate steppe, Temperate meadow-steppe etc. The raising and breeding of livestock in the study area has more than 250 kinds, mainly involving sheep, goats, cattle, buffalo, horses, donkeys, mules, and camels. Grassland based animal husbandry is the major income source of local herdsmen and accounts for more than 80% of the per capita net income of rural residents. However, by 2000 more than half of the natural grasslands in the study area were degraded to some extent (He et al., 2005; Jiang et al., 2006; Xu et al. 2007).

Many management practices have been implemented for the purposes of restoring degraded grassland, protecting natural pasture and promoting sustainable development of the region's grassland resources. A first step to relieve grazing pressure was to construct fences. Grazing prohibition, rotation or rest were implemented within the fenced grasslands. The government provided subsidies to implement these grassland management practices to realize grassland ecological protection. From these subsidies, from 2005 allowances to local herdsmen families on the Tibetan Plateau were increased by approximately 375

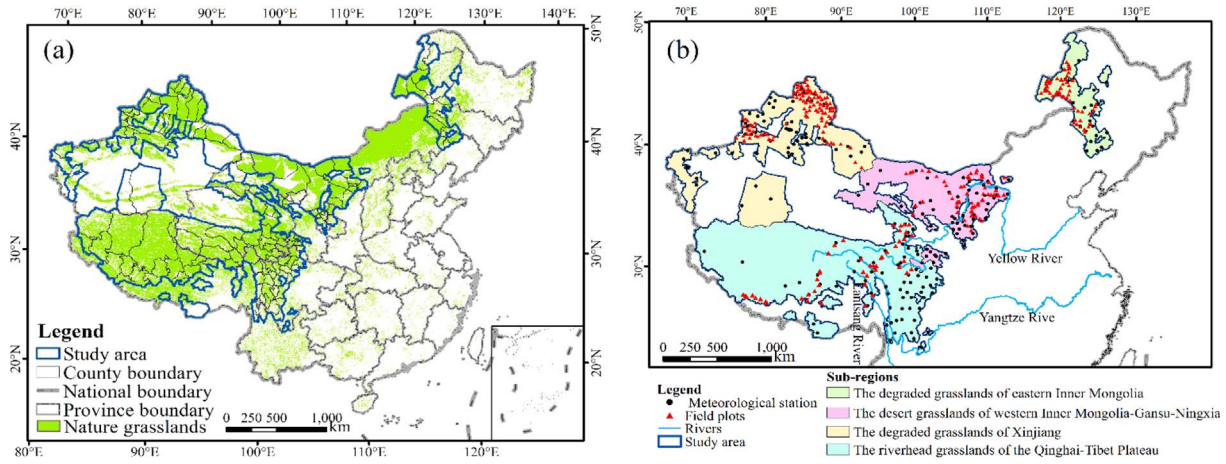

Fig. 1. (a) Geographical overview, natural grasslands, and (b) spatial distribution of meteorological stations, field plots and sub-regions in the Grazing Withdrawal Program, China.

RMB per ha every year and by approximately 300 RMB per ha every year in other areas of the study region. Further, areas have been sown with introduced pasture species for the purpose of reducing the deficit in grass production by natural grasslands. From 2011 the allowances paid to herdsmen families were increased further from the central government. Lastly, the Chinese government has provided feed grain to herdsmen when herbage from the grasslands fell below that required to maintain their livestock.

According to regional characteristics, geomorphologic units, administrative divisions, current situations, existing problems, and the needs of grassland community protection, the GWP area was divided into four sub-regions (Fig. 1b, Table 1). These sub-regions were degraded grasslands of eastern Inner Mongolia (DGEIM), desert-grasslands of western Inner Mongolia-Gansu-Ningxia (DGWIM-G-N), degraded grasslands of Xinjiang (DGXJ), and riverhead grasslands of the Qinghai-Tibet Plateau (RGQTP) (Xu et al., 2007; Zhang et al., 2016).

2.2. Meteorological data

Meteorological data included temperature, precipitation, relative humidity, wind speed, and sunlight hours from 1990 to 2013 obtained from 210 meteorological stations of the China Meteorological Data Service Center (CMDSC) (http://data.cma.cn/) (Fig. 1b). To be congruent with spatial data of ecosystem patterns and services in the study area, these data were interpolated into 1 km resolution by using ANUSPLIN version 4.2 adopting the Digital Elevation Model (DEM) data as covariant. Meteorological data derived from daily, monthly and annual data were used as input parameters to perform correlation analysis and to run models.

2.3. Ecosystem pattern change

Ecosystem pattern data in the study area with 1 km grids from 2000 to 2013 were used to analyze the spatiotemporal dynamics of each ecosystem. These data were derived from the 1:100,000-scale China Land Use/Cover Datasets (CLUDs) generated by the Chinese Academy of Sciences (Liu et al., 2005, 2014, 2016). CLUDs were interpreted from medium and high-resolution remote sensing images (Landsat TM/ETM +/OLI and HJ-1A/1B) by the human-computer interactive interpretation method (Kuang et al., 2016). They were originally divided into six classes (cropland, forest, grassland, water body, built-up area, and unused land) and 25 sub-classes (Liu et al., 2005; Zhang et al., 2014). Their accuracy was assessed by different professionals and by field verification, with the accuracies of six classes and 25 subclasses being above 94.3% and 91.2%, respectively (Liu et al., 2014). CLUDs have a national high resolution providing a long-term sequence available for continuously monitoring ecosystem dynamics. Based on the research achievement of the China ecosystem classification system (Ouyang et al., 2015; Shao et al., 2016), our study merged the CLUDs classes swampland and water body into wetland/water body, separated glacier and snow from water body, and changed unused land into desert ecosystem. This re-classification defined seven ecosystems: cropland, forest, grassland, wetland/water bodies, settlement, desert, and glacier and snow (Fig. 4).

2.4. Vegetation change

Vegetation dynamics is an important ecological process in grassland degradation and can indicate grassland degradation or restoration brought about by climate change and human activities. Fractional vegetation cover (FVC) is a comprehensive quantitative indicator that can

Table 1
Characteristics of the four sub-regions in the Grazing Withdrawal Program, China*

Sub-regions	Location	Characters/Descriptions
Degraded grasslands of eastern Inner Mongolia (DGEIM)	Inner Mongolia autonomous region	Traditional pasture with grassland animal husbandry and with water and heat for pasture growth; Provides ecological protection and defense for northern China
Desert grasslands of western Inner Mongolia-Gansu-Ningxia (DGWIM-G-N)	Inner Mongolia autonomous region, Ningxia Hui Autonomous Region and Gansu province	Belongs to the temperate zone continental dry climatic zone with serious grassland degradation, severe wind and soil erosion, and deteriorating ecological environment; The most important sand belt of northern China
Degraded grasslands of Xinjiang (DGXJ)	Xinjiang Uygur Autonomous Region	Large variations of temperature, with low rainfall and severe drought; An important area for animal husbandry with large areas of grassland and various herb types with enriched nutritive value. An important sand belt of northern China
Riverhead grasslands of the Qinghai-Tibet Plateau (RGQTP)	Qinghai Province, Tibet Autonomous Region, Sichuan province and Yunnan Province	High altitude, low annual mean temperature and precipitation with within regional difference; The headwaters of the Yangtze, Yellow, and Lantsang rivers. A core area of water regulation and soil coservation with rich biodiversity

* Data comes from the Animal Husbandry Department of the Ministry of Agriculture of the People's Republic of China (PRC).

reflect vegetation dynamics (Ivits et al., 2013). FVC was calculated from the the Normalized Difference Vegetation Index (NDVI) image dataset using the dimidiate pixel model method with the following formula:

$$FVC = \frac{NDVI - NDVI_{soil}}{NDVI_{veg} - NDVI_{soil}} \quad (1)$$

where NDVI was obtained from Moderate Resolution Imaging Spectroradiometer (MODIS) NDVI products with 1 km spatial resolution and 16-day intervals from 2000 to 2013. These data were processed by the MODIS Reprojection Tool (MRT), the Savitzky-Golay filter, projection transformation, image mosaics and Maximum Value Composites (MVC) and ultimately obtained the FVC for 15 days and one year. $NDVI_{soil}$ and $NDVI_{veg}$ represent the respective NDVI values of pure pixels of bare soil and vegetation. Their selection mainly depended on 95% confidence of NDVI pixel statistic values.

We divided the FVC change into five categories according to change of slope: obvious degradation ($slope \leq -0.46$), slight degradation ($-0.46 < slope \leq -0.02$), stable ($-0.02 < slope \leq 0.02$), slight restoration ($0.02 < slope \leq 0.46$), and obvious restoration ($slope \geq 0.46$).

2.5. Ecosystem services assessment and mapping

In order to quantify and map ecosystem services, five dominant ecosystem services were assessed based upon biophysical models and field observations. The net primary productivity (NPP) of the carbon sequestration function was simulated by the GLOPEM-CEVSA model. The water regulation function was simulated by the precipitation storage method. Wind erosion and water erosion were estimated respectively by the Revised Wind Erosion Equation (RWEQ) and Revised Universal Soil Loss Equation (RUSLE). Grassland yield was calculated from NPP data and field observation data based on the Underground Productivity Model (UPM). For the models above, all parameters were localized to improve the accuracy of results. These models were selected because they require fewer calculation parameters and are suitable for large spatiotemporal scales.

2.5.1. Carbon sequestration assessment

Defined as the carbon fixed by plants per unit time and space, net primary productivity (NPP) is an important measure of ecosystem carbon sequestration capacity and plays a significant role in the Earth's carbon cycle (Field, 1998; Lobell et al., 2002). To increase the accuracy of the estimations of ecosystem NPP, we used the integrated GLOPEM-CEVSA model. This combines the remote sensing-based GLObal Production Efficiency Model (GLOPEM) and the ecosystem process-based Carbon Exchange between Vegetation, Soil and Atmosphere model (CEVSA) in order to represent the dynamic characteristics of NPP at the regional scale (Wang et al., 2014, 2017a). The GLOPEM-CEVSA model mainly includes the satellite-derived fraction of photosynthetically active radiation absorbed by vegetation (FPAR) and relevant meteorological data.

$$NPP = GPP - R_a \quad (2)$$

$$GPP = PAR \times FPAR \times \varepsilon^* \times \sigma \quad (3)$$

$$\sigma = \sigma_T \times \sigma_E \times \sigma_S \quad (4)$$

where *FPAR* was derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) FPAR product (MOD15A2) with a spatial resolution of 1 km and a temporal scale of 8 days. R_a was autotrophic respiration. *PAR* was photosynthetically active radiation (Allan et al., 1998). ε^* was the potential conversion efficiency or carbon yield of absorbed energy. σ_T, σ_E and σ_S, respectively represent the effects of air temperature, specific humidity deficit, and soil moisture on stomatal conductance (Cao et al., 2004).

Meteorological data needed for GLOPEM-CEVSA includes interpolated air temperature, precipitation, wind speed, air relative humidity, and radiance data.

2.5.2. Water regulation assessment

The water regulation capacity of forests, grasslands, and wetland ecosystems was calculated by the precipitation storage method (Zhao et al., 2004). Formulae are calculated as:

$$Q = A \times J \times R \quad (5)$$

$$J = J_0 \times K \quad (6)$$

$$R = R_0 \times R_g \quad (7)$$

where Q is the water regulation capacity of ecosystems such as forest, grassland and wetland compared against bare land (m^3); A is different ecosystem areas (ha); J is annual output of flow rainfall (mm); R is the profit coefficient of ecosystems' decreasing runoff; J_0 is precipitation (mm); K is the percentage of annual output of flow rainfall to precipitation amounts; R_0 is the rainfall-runoff rate of bare lands in the condition of the rainfall-runoff; R_g is the rainfall-runoff rate of ecosystems in the condition of the rainfall-runoff. Specifically, based on ground surveys, remote sensing data, meteorological data, and several years of river runoff data, we improved the K value to reflect the spatial difference (Shao et al., 2016).

2.5.3. Wind erosion assessment

The RWEQ model was used to predict the wind erosion for the GWP areas from 2000 to 2013. It is an empirical-based model developed by the United States Department of Agriculture (USDA) to estimate wind erosion at a field scale and at the height of 2 m (Fryrear et al., 1998). The RWEQ model was scaled up for the regional scale and the long-term sequence to estimate the sediment transport capacity by wind (Du et al., 2016; Jiang et al., 2016a). In full consideration of factors, that include climate, soil erodibility, soil crust, surface roughness and vegetation, the RWEQ model estimated the wind erosion by GIS technologies. The RWEQ involved four basic equations as follows:

$$SL = Q_{\max}\left[1 - e^{\left(\frac{x}{s}\right)^2}\right] \quad (8)$$

$$Q_{\max} = 109.8(WF \times EF \times K' \times SCF \times COG) \quad (9)$$

$$S = 105.71(WF \times EF \times K' \times SCF \times COG) \quad (10)$$

$$SL_{sv} = SL_S - SL_V \quad (11)$$

where SL is the amount of soil transported by wind at a downwind distance of x (t/ha/yr); Q_{max} is the maximum transport capacity (kg/m); x is the distance from the upwind point of maximum wind erosion(m); S is the critical field length at which 63% of maximum transport capacity occurs; WF is the climatic factor (kg/m); EF is the soil erodibility factor (%); K' is the surface roughness; SCF is the soil crust factor; COG is the combined vegetation factor; SL_{SV} is the amount of sand fixation (t/ha/yr) that is used to evaluate the sand fixation ability of different ecosystems; SL_s is the amount of potential soil erosion under bare soil conditions; and SL_v is the lowest soil erosion under the conditions of the ground cover vegetation.

The weather factor (WF) reflects the combined effect of all kinds of meteorological factors on the wind erosion, and is expressed as follows:

$$WF = W_f \times \frac{\rho}{g} \times SW \times SD \quad (12)$$

$$W_f = \frac{\sum_{i=1}^{N} U_2(U_2 - U_t)^2 \times N_d}{N} \quad (13)$$

$$SW = \frac{ET_P - (R + I)\frac{R_d}{N_d}}{ET_P} \quad (14)$$

$$ET_P = 0.0162\left(\frac{SR}{58.5}\right)(DT + 17.8) \quad (15)$$

$$SD = 1-P(snow\ cover > 25.4mm) \quad (16)$$

where W_f is the wind factor (m^3/s^3); ρ is the air density (kg/m^3); g is acceleration due to gravity (m/s^2); SW is the soil wetness factor; SD is the snow cover factor; U_2 is the wind speed at a height of 2 m (m/s); U_t is the threshold wind speed at a height of 2 m (m/s); N_d is the number of days in the period (usually 15 days); N is the number of wind speed observations; ET_P is potential relative evapotranspiration (mm); $R + I$ is rainfall and irrigation (mm); Rd is number of rainfall and/or irrigation days; SR is solar radiation (cal/cm^2); DT is average temperature (°C); P is probability of snow depth greater than 25.4 mm. SD was calculated using the long-term snow depth dataset from the Environmental and Ecological Science Data Center for West China, National Natural Science Foundation of China (http://westdc.westgis.ac.cn); W_f and SW used the station's daily data obtained from CMDSC.

The soil erodible fraction (EF) and the soil crust factor (SCF) depend on soil texture, silt and clay content, and organic-matter content and are defined by the following equations (Fryrear et al., 1994; Zobeck, 1991):

$$EF = \frac{29.09 + 0.31Sa + 0.17Si + 0.33Sa/Cl - 2.59OM - 0.95CaCO_3}{100} \quad (17)$$

$$SCF = \frac{1}{1 + 0.0066Cl^2 + 0.021OM^2} \quad (18)$$

where Sa is the sand content (%); Si is the silt content (%); Sa/Cl is sand to clay ratio; OM is the organic matter (%); and $CaCO_3$ is the calcium carbonate fraction (%). EF and SCF were provided by the Environmental and Ecological Science Data Center for West China (http://westdc.westgis.ac.cn) and the Data Sharing Infrastructure of Earth System Science (http://www.geodata.cn).

The surface roughness (K') was related to chain random roughness and soil ridge roughness. In this study, K' was measured using a roller chain method and measured the sand and grassland roughness factors as having values of 0.96 and 0.69 respectively (Gong et al., 2014). The cropland soil roughness factor was referenced by the RWEQ model (Fryrear et al., 1998).

The combined vegetation factor (COG) includes three factors: flat residues SLR_f, standing residues SLR_s, and growing vegetation SLR_c, and is calculated by the fractional vegetation cover depending on the effect of either withered or growing vegetation on wind erosion (Gong et al., 2014). Withered vegetation cover was obtained by field observation combining visual estimation and traditional photographic recording. The growing vegetation cover was derived from remote sensing data (see Section 2.4).

$$\mathrm{SLR}_f = e^{-0.0438(SC)} \quad (19)$$

$$\mathrm{SLR}_s = e^{-0.0344(SA^{0.6413})} \quad (20)$$

$$\mathrm{SLR}_c = e^{-5.614(CC^{0.7366})} \quad (21)$$

where SC is the soil surface area covered by flat residues (%); SA is the silhouette area computed by multiplying the number of standing stalks in 1 m^2 times their average diameter (cm) and times their stalk height (cm); CC is the growing vegetation cover.

2.5.4. Water erosion assessment

Water erosion, calculated using the Revised Universal Soil Loss Equation (RUSLE), included the rainfall erodibility factor (R), the soil erodibility factor (K), the slope length factor (L), the steepness factor (S), the cover-management factor (C), and the support practice factor (P) (Renard et al., 1997). The equation is:

$$A = R \times K \times L \times S \times C \times P \quad (22)$$

where A is the average soil loss that is the water erosion module (t/ha/yr); R (MJ·mm/(ha·h·yr)) was calculated by a rainfall erosivity model using daily rainfall amounts originally obtained from CMDSC (Zhang et al., 2002). K (t·h/(MJ·mm)) was estimated by the Nomo model based on the 1:1 million soil data; L (m) and S (%) is calculated by the core algorithm from SRTM3 V4.1 (Liu et al., 2000; McCool et al., 1987) and the method improved by considering runoff barriers of land surface parameters; C was calculated based on FVC, and time intervals for both rainfall erodibility and fractional coverage factors determined for 16 days to avoid time asynchronism and to reduce errors. P was mainly determined from relevant literature and expert consultations, with P values of grassland, forest and bare land set at 1, paddy fields at 0.15, dry land at 0.352, settlement at 0.01, and wetland/water bodies at 0.

Quantitative analysis of soil retention assessed the ability of vegetation and soil control practices to capture and retain soil. Soil retention (A_G) was defined as the soil loss in conditions of extreme degradation minus the soil loss with the current land use/land cover (Jiang and Zhang, 2016). The following formulae were used:

$$A_D = R \times K \times L \times S \times C_D \times P \quad (23)$$

$$A_R = R \times K \times L \times S \times C_R \times P \quad (24)$$

$$A_G = R \times K \times L \times S \times (C_D - C_R) \times P \quad (25)$$

where A_D is the soil loss (t/ha/yr) in conditions of extreme degradation without vegetation cover and A_R is the soil loss with the current land cover and management conditions.

2.5.5. Grassland yield assessment

Grassland yield (GY) is a quantitative measure of grassland production functions and the ability of grassland ecosystems to maintain sustainable development. GY in the GWP areas for different grasslands during 2000–2013 was calculated from NPP and field measurements. GY was estimated by the Underground Productivity Model (UPM) defined by Fan et al. (2010) and Gill et al. (2002). Field measurements of belowground biomass (BGB) and aboveground net primary productivity (ANPP) for the main grassland types, e.g., Alpine steppe, Alpine meadow, Temperate desert, Temperate steppe, Temperate meadow-steppe were obtained from field sampling during the period of 2004–2013 (Fig. 1b) (Fan et al., 2008; Fan et al., 2016). Vegetation biomass was weighed after 48 h of drying in an oven set at 65 °C and GY was presented as dry biomass. The ratio of living belowground biomass to total belowground biomass ($LBGB$) was obtained by cyclic sampling. The distribution and areas of the grassland types were determined from the 1:1 million Chinese grassland resources map (ECAGRC, 1993).

2.6. Change trends of relevant indices

The linear slopes of FVC, ecosystem services and climatic factors over time can depict changing trends and the geographical differences more effectively and precisely (Ma and Frank, 2006). The slope of the linear time trend was calculated for certain periods and for each pixel by ArcGIS. According to the following formula:

$$Slope = \frac{n \times \sum_{i=1}^{n} i \times X_i - (\sum_{i=1}^{n} i)(\sum_{i=1}^{n} X_i)}{n \times \sum_{i=1}^{n} i^2 - (\sum_{i=1}^{n} i)^2} \quad (26)$$

where i is 1 for the first year, such as 1990 or 2000, 2 for the next year, such as 1991 or 2001, and so on; n is the study period, such as 24 or 14 years; X_i is the value of the FVC and each ecosystem service for year i. Negative values of the slope represent the occurrence of degradation and positive values indicate an overall increase or restoration trend.

2.7. Ground survey and field observation

To localize key model parameters and to verify the results of model simulations, from 2004 to 2013 we obtained hundreds of data samples from 270 field points for vegetation productivity, plant compositional structure, soil properties, grassland degradation, hydrology, and meteorology (Fig. 1b). With reference to grassland types and the utilization intensity and management of grassland, grassland plots were

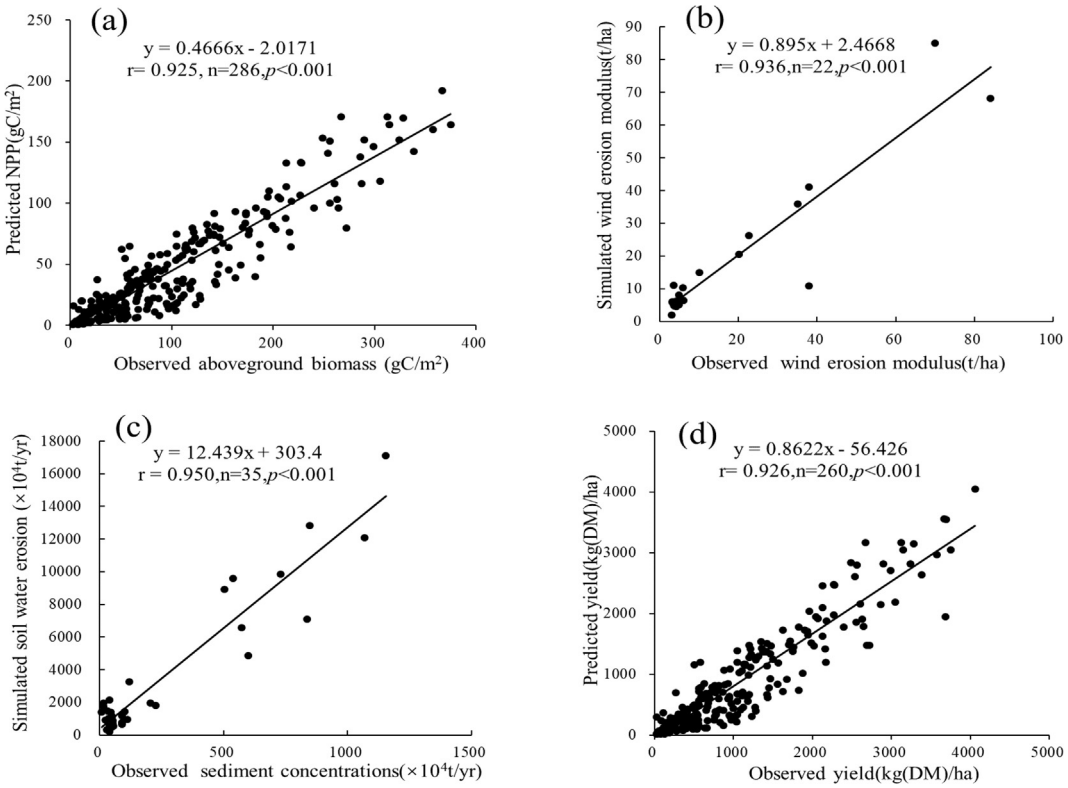

Fig. 2. Comparisons of simulated data and observation data of the Grazing Withdrawal Program, China. (a) NPP, (b) wind erosion, (c) water erosion, (d) grassland yield.

located to investigate and verify NPP and grassland yield simulation results (Fig. 2a, d) (Fan et al., 2008, 2010; Wang et al., 2017a; Zhou et al., 2016). We investigated the wind erosion of RWEQ by means of ^{137}Cs measurements mainly at sites the Inner Mongolia (Fig. 2b) (Chi, 2015). The wind/water erosion modulus is defined as the amount of soil loss by wind/water per unit area of time. We validated the results of RUSLE by annual sediment concentrations from major national hydrological stations and other research studies (Fig. 2c) (Liu et al., 2016; Shao et al., 2016). Further, results of these models were compared with results of previous studies.

3. Results

3.1. Climate variability

The climate in the study area showed a trend of becoming wetter and warmer from 1990 to 2013 (Fig. 3a, c). From an analysis of the climate of this 24 year long period, precipitation and temperature respectively showed an increasing trend of 1.51 mm/yr and 0.04 °C/yr. To highlight climate variability with time, during 2000–2013, precipitation showed an increasing trend of 2.43 mm/yr, which was larger than that in 1990–1999 whereas temperature showed a trend increase of 0.03 °C/yr, which was lower than that in 1990–1999.

For sub-regions (Fig. 3b, d), the DGEIM had suitable hydro-thermic factors for grassland vegetation with annual precipitation of 392.1 mm and mean annual temperature of 1.2 °C. The DGWIM-G-N and DGXJ had similar annual precipitation of about 199 mm, and their mean annual temperatures were 6.4 °C and 4.1 °C, respectively. The RGQTP, located in high altitudes, had the lowest mean annual temperature of −1.9 °C and an annual precipitation of 470.5 mm.

3.2. Ecosystem pattern change

In 2013, the grassland ecosystem area was 185.7×10^4 km^2 forming the largest proportion (57.2%) of the GWP area. The proportions of areas characterized as desert and forest ecosystems were also high, covering 24.3% and 8.7% of the GWP respectively. The other ecosystem types, including cropland, wetland/water body, settlement and glacier and snow, together covered 9.7% of the area (Fig. 4a). The seven ecosystems had regional discrepancy in their spatial distribution. Grassland was distributed over the whole study area but more was located in the Qinghai-Tibet Plateau. Desert ecosystem was mainly located in central regions of the DGWIM-G-N and the DGXJ. Forest ecosystem was concentrated in the east of the DGEIM.

According to the analysis of the main grassland transformations (Fig. 4b), the grassland area had a net decrease of 25.7×10^4 dataset using the dimidiate pixel km^2, a reduction of 12.2% from 2000 to 2013. The newly restored grassland area was 12.2×10^4 km^2, while 37.9×10^4 km^2 of grassland was converted to other ecosystems. Conversion from desert, forest, glacier and snow, and cropland, respectively accounted for 38.7%, 27.3%, 17% and 8.9% of the newly developed grassland. For the 14 year period, grassland desertification was the most significant ecosystem transformation, with 22.8×10^4 km^2 of grassland lost. The gain of grassland by conversion was 4.7×10^4 km^2. The distribution of the decrease of the area of grassland was 35.7% to desert, 31% to wetland/water body, 14.2% to forest and 8.9% to cropland. The spatial distribution of grassland changes was fragmented and showed a spatial differentiation pattern (Fig. 4b). Grassland increase was distributed mainly in northern areas of the DGXJ. Grassland decrease occurred mainly in Northern Tibetan Plateau and marginal desert areas of the DGWIM-G-N and the DGXJ.

3.3. Carbon sequestration change

Between 2000 and 2013, the average carbon sequestration was 149.6 gC/m^2/yr, and this increased annually by an average of 0.8 gC/m^2. The average annual carbon sequestration was about 47.7 billion gC/yr. Among the four sub-regions (Fig. 5, Table 2), the average annual carbon sequestration of the DGEIM had the highest value (431.2 gC/m^2) with an increasing trend of 1.2 gC/m^2/yr. The average annual

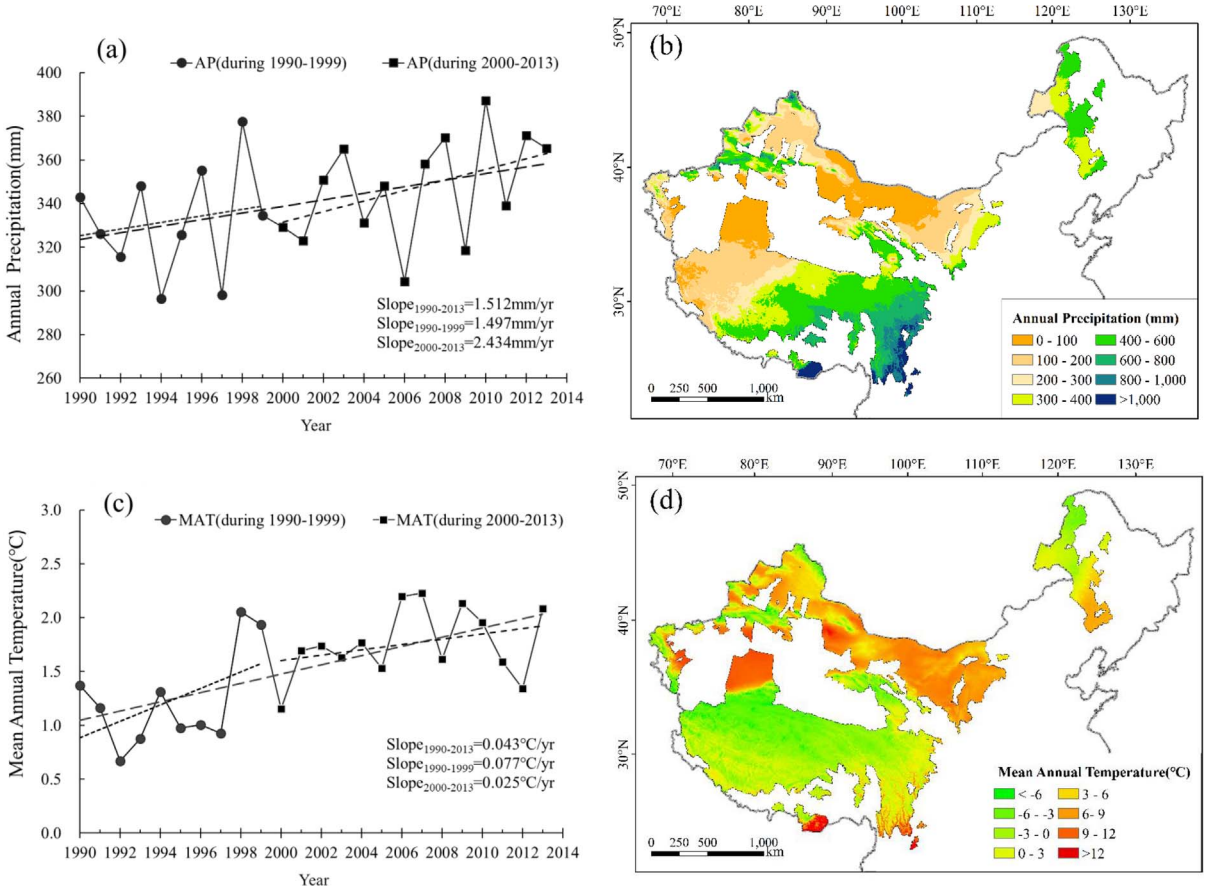

Fig. 3. Temporal variations and spatial distributions of (a and b) Annual Precipitation (AP) and (c and d) Mean Annual Temperature (MAT) of the Grazing Withdrawal Program, China from 1990 to 2013.

carbon sequestration of the DGWIM-G-N was the lowest (84.1 gC/m^2) but the region had a higher increasing trend of 1.3 gC/m^2/yr.

3.4. Water regulation change

Water regulation in forest, grassland and wetland/water body ecosystems improved from 616.8 m^3/ha/yr in 2000 to 632.7 m^3/ha/yr in 2013. Over this period, the average annual water regulation volume was about 139 billion m^3/yr, with an increasing trend of 0.17 billion m^3/yr. Being mainly affected by the distribution patterns of precipitation and ecosystems, water regulation had an obvious regional difference, generally decreasing from east to west (Fig. 6a). As for sub-regions (Fig. 6b, Table 2), the average annual water regulation volume of the RGQTP reached a maximum value at 99.5 billion m^3/yr and occupied nearly 72% of the total annual water regulation of the study area. The per unit amount of annual water regulation in the DGEIM represented the highest value with 788.3 m^3/ha/yr and the largest trend of 6.8 m^3/ha/yr. However, only the water regulation volume of the DGXJ showed a decreasing trend with a slope of −4.2 m^3/ha/yr.

3.5. Sand fixation change

From 2000 to 2013 the annual average wind erosion modulus in the GWP areas was 26.7 t/ha (Fig. 7a). The wind erosion modulus showed spatial heterogeneity and was distributed mainly in deserts and sandy lands where wind erosion frequently occurred. DGWIM-G-N had the

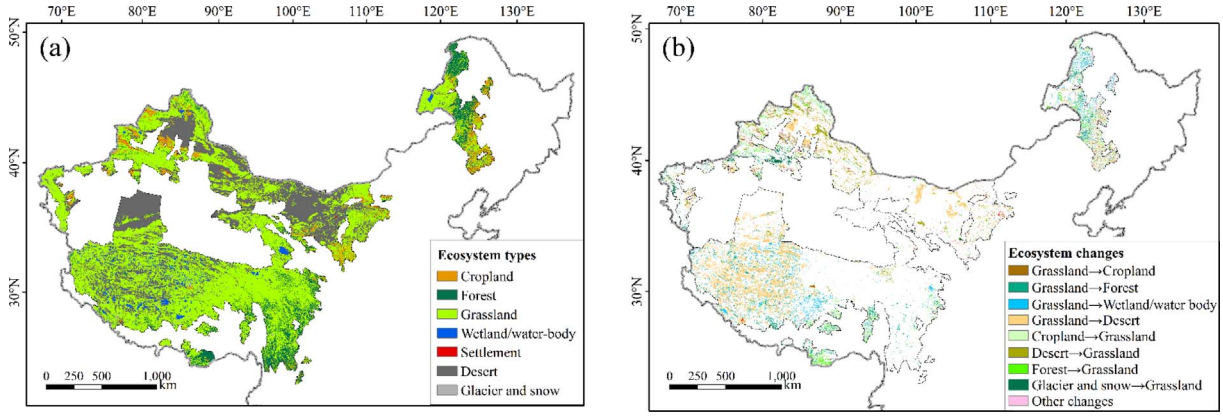

Fig. 4. (a) Distribution map of ecosystems in the Grazing Withdrawal Program, China in 2013, (b) the areas of main grassland transformations from 2000 to 2013.

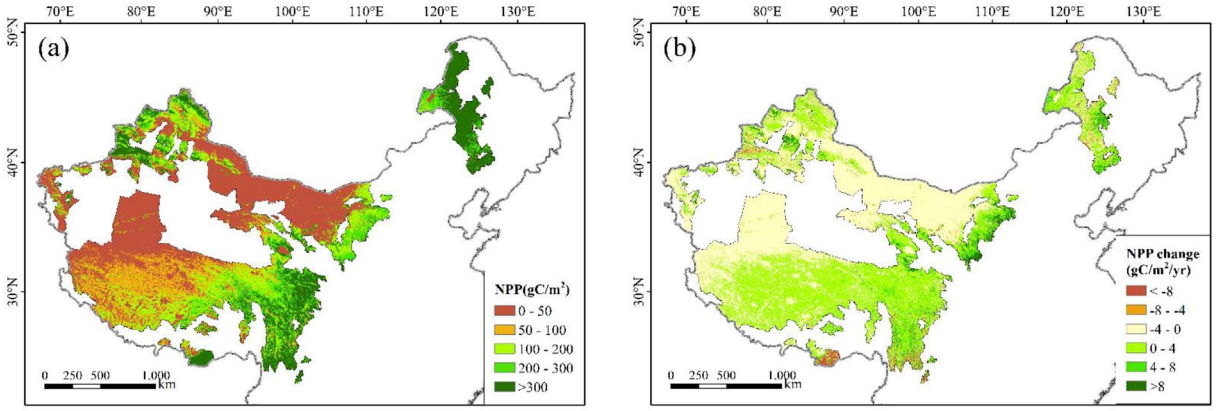

Fig. 5. Map of (a) spatial differences of carbon sequestration and (b) and rates of change of carbon sequestration for the Grazing Withdrawal Program, China in 2000–2013.

Table 2
The characteristics of the key ecosystem services for the four sub-regions of the Grazing Withdrawal Program, China. *Note* (Sub-region names): Degraded grasslands of eastern Inner Mongolia (DGEIM), Desert grasslands of western Inner Mongolia-Gansu-Ningxia (DGWIM-G-N), Degraded grasslands of Xinjiang (DGXJ), Riverhead grasslands of the Qinghai-Tibet Plateau (RGQTP).

Ecosystem services	Parameters		DGEIM	DGWIM-G-N	DGXJ	RGQTP
Net primary productivity	Mean annual values	(gC/m^2)	431.2	84.1	96.9	156.5
	Slope	($gC/m^2/yr$)	1.2	1.3	0.3	0.8
Water regulation	Mean annual values	(m^3/ha)	788.3	306.1	300	732.3
	Slope	($m^3/ha/yr$)	6.8	0.5	−4.2	1.1
Sand fixation	Mean annual values	(t/ha)	52.0	54.8	19.1	34.0
	Slope	(t/ha/yr)	−1.2	−1.9	−1.4	0.2
Soil retention	Mean annual values	(t/ha)	5.6	10.1	13.2	42.5
	Slope	(t/ha/yr)	0.5	0.4	0.2	0.3
Grassland yield	Mean annual values	(kg/ha)	1398.5	694.4	637.7	772.1
	Slope	(kg/ha/yr)	16.1	4.2	11.1	6.2

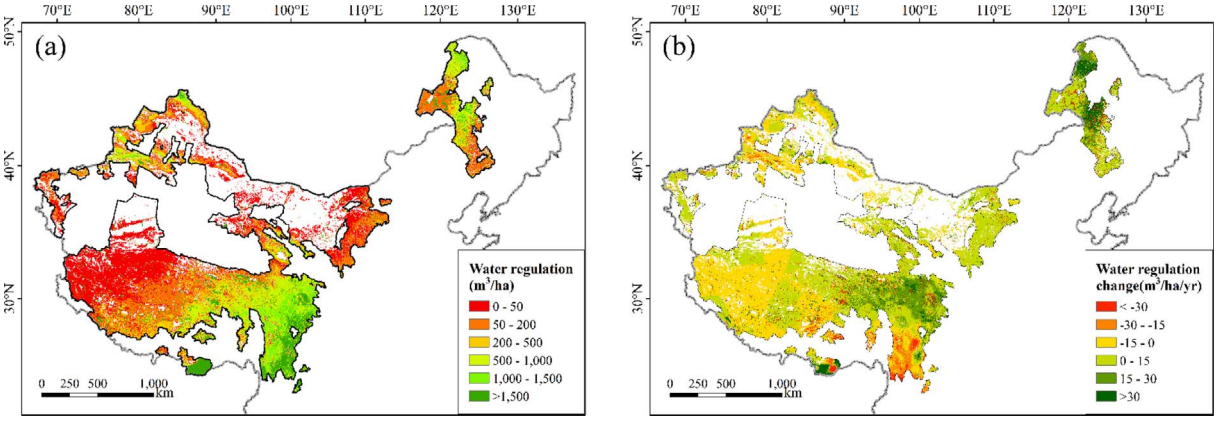

Fig. 6. Map of (a) spatial difference of water regulation and (b) rates of change water regulation for the Grazing Withdrawal Program, China in 2000–2013.

highest wind erosion modulus of 56.3 t/ha. The DGEIM had the lowest annual average wind erosion modulus (4.4 t/ha). Over the 14 years, the annual average wind erosion modulus showed a decline of −1.1 t/ha/yr, with the biggest change for DGWIM-G-N (Fig. 7b). The decline in annual wind erosion modulus accounted for 66% of the whole study area.

The average annual sand fixation in the GWP areas was 11.2 billion t/yr, and the per unit amount was 35.2 t/ha (Fig. 7c). For the average annual sand fixation of each region (Table 2), that of the DGWIM-G-N was the highest at 54.8 t/ha and that of the DGXJ was the lowest at 19.1 t/ha. The amount of sand fixation decreased with a slope of −271 million t/yr (Fig. 7d). The average annual sand fixations of DGWIM-G-N and the DGXJ decreased obviously with slopes of 118.1 million t/yr and 120.7 million t/yr, respectively. That of DGEIM decreased with a slope of 31.6 million t/yr, and only RGQTP showed the increasing trend of 28.9 million t/yr.

3.6. Soil retention change

From 2000 to 2013, the average annual soil water erosion modulus in the GWP areas was 21.26 t/ha and the soil water erosion amount was 6.7 billion t/yr (Fig. 8a). From the spatial distribution, water erosion that was driven by precipitation patterns was more serious in the southeast of the GWP areas (Fig. 8b). The average annual soil water erosion modulus of the RGQTP had the highest level at 34.2 t/ha, and that of the DGEIM had the lowest level at 5.1 t/ha. For the 14 years, soil water erosion showed a slight upward trend of 319.2 million t/yr.

The average annual soil retention in the GWP areas was 8.1 billion t/yr, and the per area amount was 25.6 t/ha (Fig. 8c). The average annual soil retention of the RGQTP remained highest (42.5 t/ha). Soil retention fluctuated year by year but showed an overall positive trend ranging from 25.2 t/ha in 2000 to 28.5 t/ha in 2013, an increase of

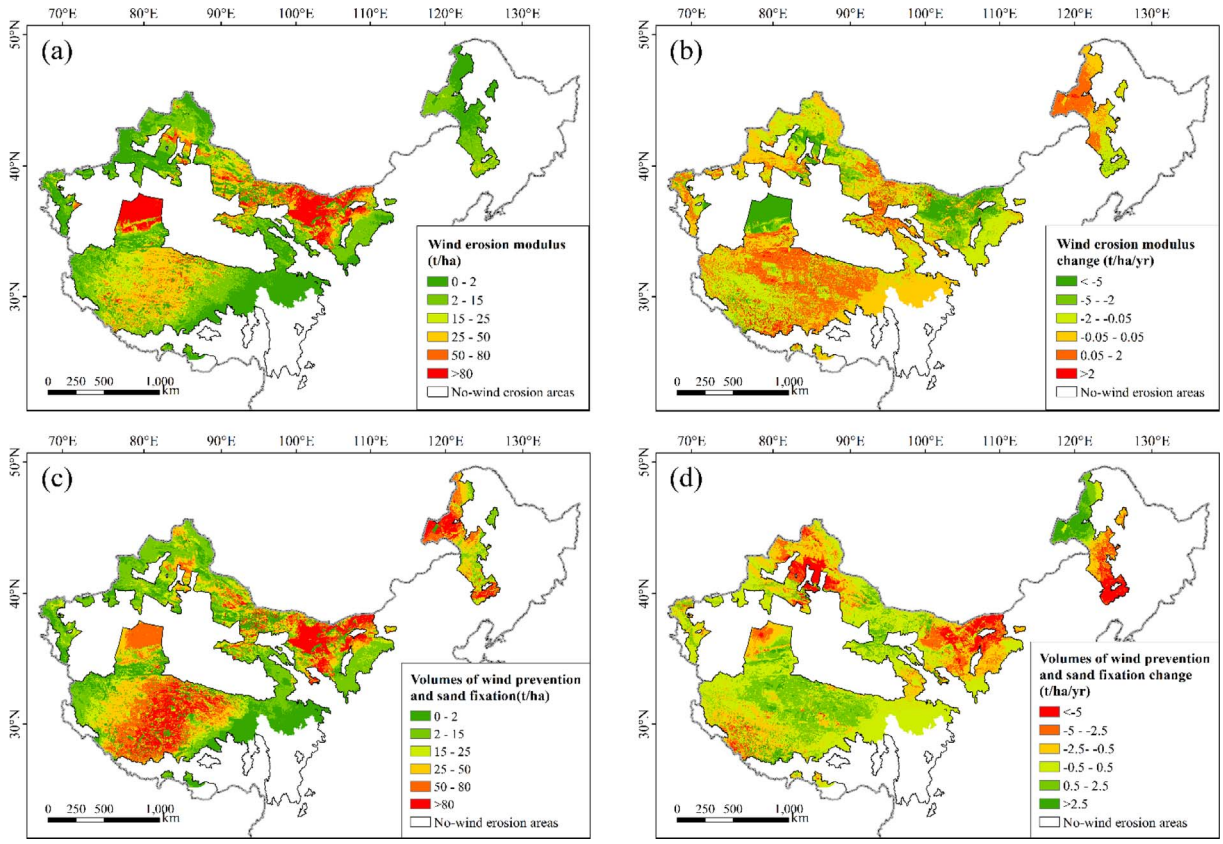

Fig. 7. Distribution maps (a and c) and spatial difference (b and d) of wind erosion and sand fixation for the Grazing Withdrawal Program, China in 2000–2013.

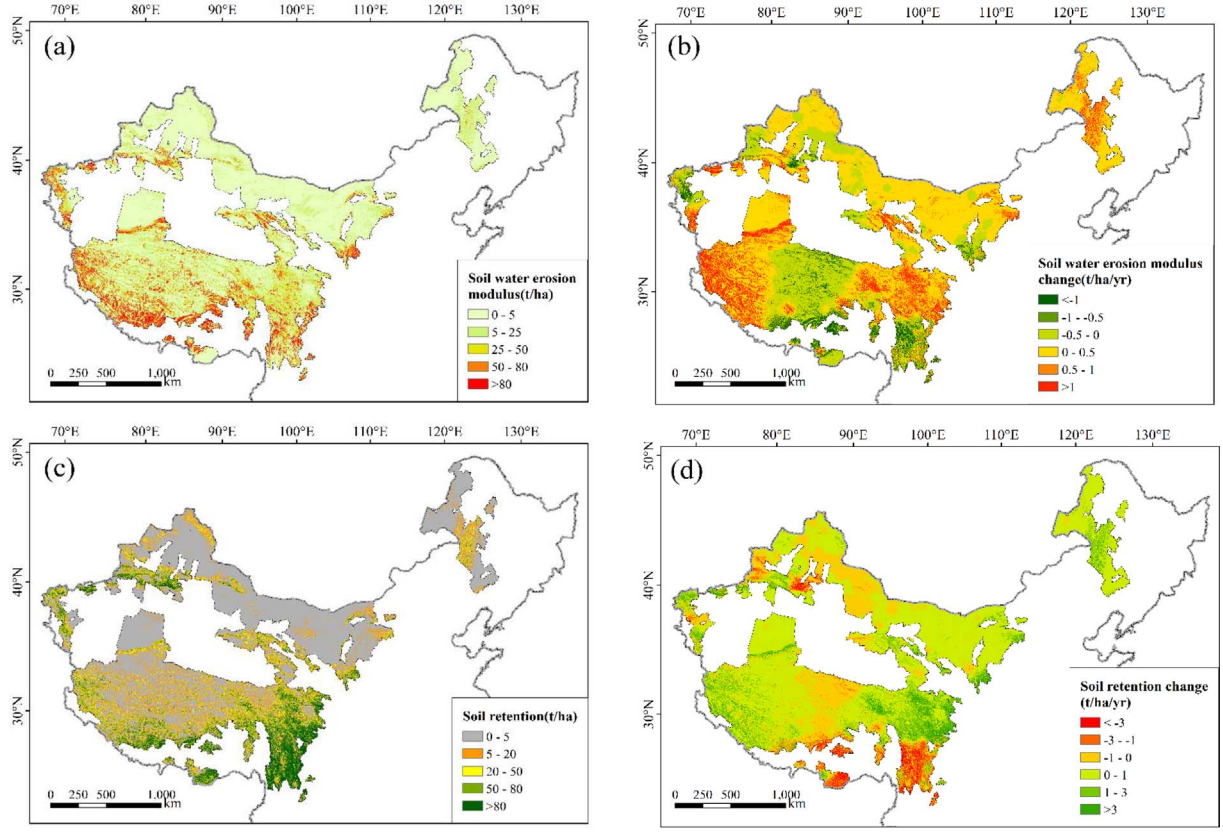

Fig. 8. Distribution maps (a and c) and spatial differences (b and d) of water erosion and soil conservation for the Grazing Withdrawal Program, China in 2000–2013.

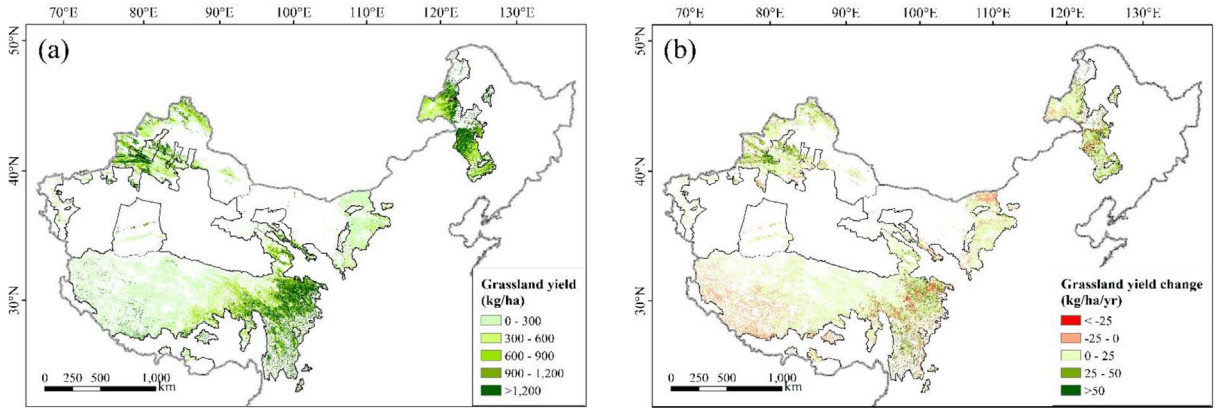

Fig. 9. Map of (a) spatial difference of grassland yield and (b) rates of change grassland yield for the Grazing Withdrawal Program, China in 2000–2013.

13.3%. Most of the regions had some improvement of soil retention, only the southeast region of the RGQTP showing an obvious decrease (Fig. 8d, Table 2).

3.7. Grassland yield change

The average annual GY in the GWP areas from 2000 to 2013 was 819.6 kg /ha with a fluctuating but progressive increase of 8.3 kg /ha/yr (Fig. 9a). Annual GY of DGEIM had the highest value of 1398.5 kg /ha with an obvious increasing trend of 16.1 kg /ha/yr. The GY in some areas of the DGWIM-G-N and the RGQTP only appeared to have a moderate decline (Fig. 9b, Table 2).

4. Discussion

4.1. Factors driving the ecosystem services

On a large-scale the major factors that influence ecosystem services mainly include ecosystem pattern change, climate variability and ecological restoration programs (Jiang et al., 2016a). Through comparisons between different ecosystems and multiple ecosystem services of their temporal and spatial changes for the GWP areas during 2000–2013, we found that changes in the areas of the ecosystems directly affected ecosystem services. The more frequently ecosystems were transformed from one to another, especially on the edges of deserts and sand lands, the more significant was the decline of ecosystem services. However, ecosystems change rates were very low, we focused on analyzing the impacts of climate variability and effective implementation of ecological restoration programs on ecosystem services.

4.1.1. Effects of climate variability

Temperature and precipitation play a key role in soil erosion, hydrological process and vegetation growth. Multiple ecosystem services gradually decreased from the southeast to the northwest, corresponding with gradients in climate variability. During 2000–2013 the wetter and warmer climate improved vegetation growth and productivity. Mainly due to sufficient water supply and warmer temperatures, NPP and GY were enhanced by increasing photosynthesis and carbon sequestration. The area of wetland /water body increased by 5.2×10^4 km^2 from 2000 to 2013, an overall increase of 57.7%, and water regulation amounts also improved.

As indicated in Section 2.5, vegetation cover, wind speed (W factor) and rainfall erosivity (R factor) for the parameters in the RWEQ and RUSLE models exhibited considerable variations. Other factors (soil characteristics, topographic factors, etc.) remained relatively stable. Although the annual mean wind factor for the entire area decreased at the low rate of -1.77 m^3/s^3, reduction of the wind factor (Fig. 10a) greatly affected wind erosion in local areas, especially in the DGWIM-G-N. Lower levels of wind speed were often accompanied by reduced frequency in the occurrence of sandstorms, thereby further lowering wind erosion. The wind erosion modulus decreased significantly under the condition of vegetation cover surface. Although the amount of sand fixation decreased relatively, this did not mean decrease in the service capability of sand fixation. Considering the climatic driving forces, a weakening trend of sand fixation was associated with a decrease of the annual average wind factor. In addition, increased precipitation promoted the resistance of soil to wind erosion and enhanced sand-fixing function.

Precipitation was the factor most directly affecting water regulation and soil retention. In the DGEIM and east areas of the RGQTP, the

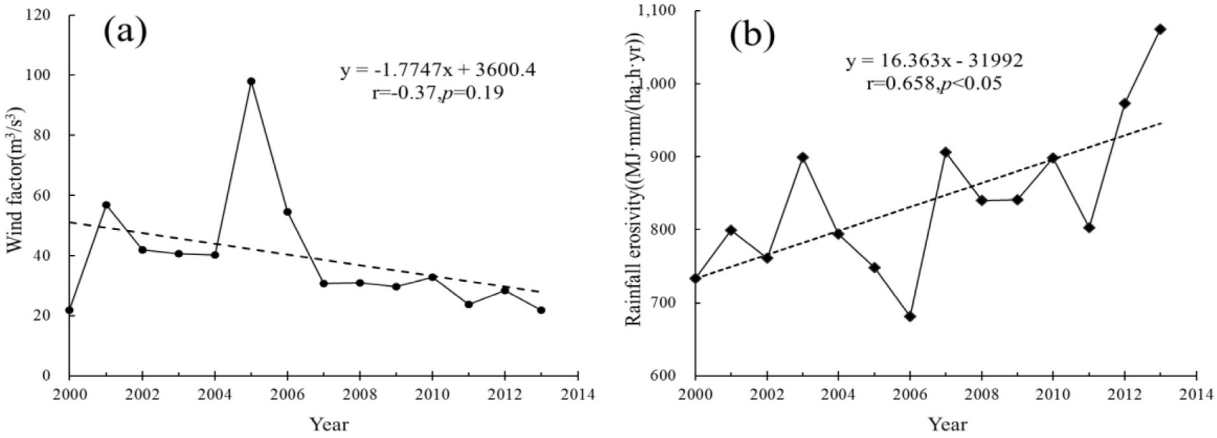

Fig. 10. Temporal changes of (a) annual mean wind factor and (b) rainfall erosivity for the Grazing Withdrawal Program, China in 2000–2013.

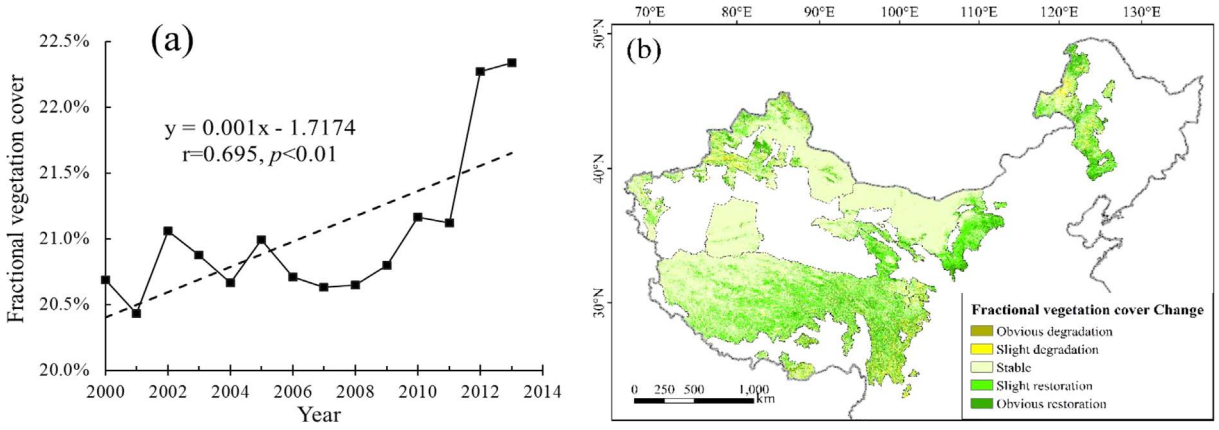

Fig. 11. (a) Temporal changes, and (b) spatial difference in the vegetation cover for the Grazing Withdrawal Program area, China in 2000–2013.

increase in precipitation led to the increase in water regulation, whereas in the northwest of the RGQTP and central areas of the DGXJ, as precipitation decreased, water regulation appeared to decline. Because precipitation was the major erosive force, as precipitation in the GWP areas increased from 2000, there was a significant increase in rainfall related erosion (Fig. 10b), to a certain extent resulting in further increasing trend of water erosion.

4.1.2. Effects of human activities

We found that changes of ecosystem services were caused by human activities, principally overgrazing, conversion of grassland to other ecosystems, and ecological restoration programs.

Overgrazing is generally considered the major driver of grassland degradation, leading to severe limitation of ecosystem services, reducing vegetation productivity and accelerating soil erosion (Wu and Tiessen, 2002). Grazing by domestic livestock can modify and damage soil surfaces and destroy soil crusts by their treading. The gradual reduction of grassland area and increased livestock number led to more grassland degradation (Yang, et al., 2016).

In responding to the demand of faster socio-economic development, human-caused ecosystem changes could also significantly cause decline of ecosystem services, especially in the DGXJ, by reducing water regulation and sand fixation (Figs. 6 and 7). Cropland increased by 19.5% replacing 2.5×10^4 km^2 of grassland from 2000 to 2013. Grassland reclamation destroyed soil surface structure, reduced soil fertility, and increased soil bulk density, resulting in the exacerbation of wind erosion (He et al., 2005). Moreover, continuously lowering groundwater by pumping for irrigation, leads to the formation of funnel regions and shrinkage of wetlands that ultimately will reduce water regulation. Further, urbanization and population growth with rapid increase of urban built-up and rural settlement areas, and the exploitation of mineral resources encroached further onto grassland and cropland. Quantitative analysis indicates the change rate of settlement increased up to 4.6%/yr (Fig. 4). In general, more extensive and intensive urban infrastructure development, long-term unregulated mining, and construction of roads and facilities can further reduce ecosystem services.

However, for the GWP areas, ecological restoration programs have become the main human activities and have achieved positive improvements for some ecosystems (Zhang et al., 2016). After the implementation of the GWP, through grazing prohibition, rotation or resting from livestock grazing overloading rates declined progressively in the main pastoral provinces. This effectively reduced grazing pressure and promoted grassland vegetation restoration. Survey showed that vegetation coverage, height, and fresh grass yield in the GWP region had a larger positive increase than those of other regions (Liu, 2015). As well as the GWP, some other ecological restoration programs, particularly the GGP, the BTWSSCP, and the ESAS, were also carried out in the area of the GWP and also enhanced key ecosystem services (Cao, 2011; Lü et al., 2012; Wu et al., 2013). In summary, comprehensive implementation of ecological restoration programs may have a large effect on the increasing trend of vegetation activity and improvement of multiple ecosystem services.

4.1.3. Vegetation restoration/degradation

Climate variability, as well as ecological programs, has a great effect on vegetation activity. The assessment of vegetation restoration is usually regarded as an important index for assessing the success or failure of ecological programs.

From 2000 to 2013, areas with vegetation cover restoration trends (slight + obvious) accounted for approximately 30.5% of the area GWP, whereas the vegetation cover showed a decreasing trend (slight + obvious degradation) for only 4.6% of the area (Fig. 11). These changes indicate that vegetation recovery may be achieved by the combined effects of a change to a wet-warmer climate and the implementation of ecological programs. The joint effects of climate variability and ecological restoration programs promoted the spatio-temporal dynamics of FVC. Measured suction in soils covered by vegetation is considerably higher than that in bare soil. Vegetation not only contributes to soil strength enhancement through mechanical reinforcement by roots, but also induces suction via evapotranspiration to influence the retention capacity of the soil system (Garg et al., 2017). Moreover, suction induced on vegetated slopes are relatively higher than those on bare slopes (Das et al., 2018). Thus vegetation restoration partly explains the enhancements of multiple ecosystem services.

4.2. Synergies and tradeoff between ecosystem services

Different ecosystem services correlate with each other and trade-offs and synergies exist at different space-time scales (Bennett et al., 2009). NPP, water regulation and grassland yield experienced a significant increase for most of the GWP area (Sections 3.3–3.7). These correlated changes may indicate that these three key ecosystem services acted in synergy. In addition, especially with increasing precipitation, both water regulation and soil retention followed a trend of increase.

Soil erosion mainly includes both wind and water erosion, so soil conservation capacity is mainly reflected in the sand fixation and soil retention. Comparing the spatial distribution of the wind (Fig. 7a) and water erosion (Fig. 8a) modulus, we found the regions with higher wind erosion modulus did not suffer from the severer water erosion hazard. Most significantly of all, the annual wind erosion modulus in DGWIM-G-N was above 80 t/ha/yr, whereas the water erosion modulus of that region ranged from just 0 to 5 t/ha/yr. The average annual sand fixation and soil retention of the region also showed the same change tendency. Consequently, the decrease in regional sand fixation and the improvement in soil retention may be considered a tradeoff.

4.3. Limitations and future research in ecosystem services assessment

The accuracy of the scope of the GWP could be usefully improved. Due to a lack of relevant data, the specific scope of the GWP implementation is not quantified as it only assembles information from within the boundaries of key implementation counties. In addition, there are other ecological programs in the GWP areas, so the ecosystem services changes that our study indicates are the combined results of all the ecological programs and climate changes contained in the full area (Fig. 1).

The quantification of ecosystem services on large scales mainly lack reliable data, a unified estimation method, and indication of result accuracy. The sampling locations emphasized grassland sites and did not sufficiently account for other ecosystem sites. More field experiment sites should be considered in future research. All the methods of estimating multiple ecosystem services may introduce uncertainty and errors. These can be reduced by using more field observation data, higher spatial and temporal resolutions in remote sensing data, and more accurate localization parameters (Jiang and Zhang, 2016). For more rigorous conclusions to be obtained, further studies are needed by systematic conducting of probabilistic analysis of measured soil properties, e.g. soil suction (spatial and temporal variation) in the field for vegetated slopes (Hazra et al., 2017), and assessment of the impact of vegetation induced suction and bivariate on the stability of vegetated slopes (Das et al., 2018). A deeper understanding of the influence of biophysical processes on ecosystem services spatiotemporally is required. Seeking the interactions and trade-offs among ecosystem services will be conducive to maximizing ecosystem benefits to human well-being.

4.4. Sustainability through adaptive management

Ecological restoration programs are effective strategies for reversing deteriorated grassland and improving ecosystem services. The current ecological restoration results still remain localized and temporary, and fundamentally do not improve their effects (Jiang et al., 2016b; Shao et al., 2016). Furthermore, the service function of sand fixation did not show significant improvement. Therefore, the implementation of further ecological projects, similar to the GWP, is necessary to progress. The annual output value of animal husbandry of China in 2016 reached 312 billion RMB. Development of animal husbandry has a significant impact on people's livelihood especially in the pastoral areas. Further, efforts should be made to plan the management of China's grassland resource in accordance with the principle of 'utilization through protection and protection through utilization'. Forage supply and animal balance is the core issue of grassland resource protection and the development of animal husbandry. Hence, grazing pressure monitoring and livestock management play critical parts in grassland vegetation restoration.

Furthermore, people have a preference for specific kinds of ecosystem services, and this causes trade-offs and synergy among different kinds of ecosystem services. In the future, we should aim to qualitatively discriminate with relatively precise estimation the correlations among different kinds of ecosystem services.

5. Conclusions

Using meteorological data, remote sensing data, and field observations, this study applied several models to assess the spatial and temporal changes of multiple ecosystem services in the GWP areas from 2000 to 2013. The main conclusions are as follows. Ecosystem pattern remained relatively stable during 2000–2013. The concrete features were that: grassland area showed no marked change; wetland/water body had slight expansion; and desert expansion showed a slower trend. Key ecosystem services in the GWP areas showed overall improvement but with localized deterioration. Overall NPP and GY increased remarkably and showed similar spatial variation characteristics. Water regulation in forest, grassland and wetland/water body ecosystems improved slightly. Although sand fixation showed a slight decreasing trend, the areas with high wind-erosion risk appeared to decline for over half of the whole study area. The amount of soil retention increased by 13.3% and the soil conservation ability has been improved. Furthermore, we found there were synergy among carbon sequestration, water regulation and grassland yield, and trade-off between sand fixation and soil retention. Spatiotemporal variations of multiple ecosystem services were greatly influenced by spatial heterogeneity. Among the four sub-regions, the ecosystem services conditions ranked as follows: DGEIM > RGQTP > DGXJ > DGWIM-G-N. The water regulation capacities of forest, grassland and wetland/water body ecosystems had all improved positively through increased precipitation and vegetation recovery. The overall trend of sand fixation amount went down due to reduced wind erosion and increased vegetation cover. Enhancing rainfall erosivity can partly explain the increment in soil erosion amount. Ecosystem status improved mainly due to the warmer and wetter climate variability and the positive effects of ecological conservation and restoration projects.

Overall, the GWP has had comparatively successful achievements and has met its objectives. As well, with the change towards warmer and wetter climate, human activities appear to have had positive impacts on ecosystem services as well. However, grassland degradation still continues and the effectiveness of ecological projects is likely a temporary improvement rather than fundamental change. Ecological programs should continue to advance further to obtain fundamental improvement of China's ecological situation.

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References

Allan, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements. FAO Irrigation and Drainage Paper No. 56. FAO 56.

Bao, Z.W., Zhang, S.Y., 2015. Analysis on the implementation effects of the policy of compensation to and rewarding for grassland eco-protection-taking chifeng. J. Anhui Agric. Sci.

Bennett, E.M., Peterson, G.D., Gordon, L.J., 2009. Understanding relationships among multiple ecosystem services. Ecol. Lett. 12, 1394–1404.

Cao, M., Prince, S.D., Small, J., Goetz, S.J., 2004. Remotely sensed interannual variations and trends in terrestrial net primary productivity 1981-2000. Ecosystems 7.

Cao, S., 2011. Impact of China's large-scale ecological restoration program on the environment and society in arid and semiarid Areas of China: achievements, problems, synthesis, and applications. Crit. Rev. Environ. Sci. Technol. 41, 317–335.

Chen, H., Shao, L., Zhao, M., Zhang, X., Zhang, D., 2017. Grassland conservation programs, vegetation rehabilitation and spatial dependency in Inner Mongolia, China. Land Use Policy 64, 429–439.

Chi, W., 2015. Research on spatial-temporal characteristics of soil wind erosion and ecosystem service of soil conservation in Inner Mongolia Plateau. University of Chinese Academy of Sciences, Beijing.

Das, G.K., Hazra, B., Garg, A., Ng, C.W.W., 2018. Stochastic hydro-mechanical stability of vegetated slopes: An integrated copula based framework. Catena 160, 124–133.

Du, H., Dou, S., Deng, X., Xue, X., Wang, T., 2016. Assessment of wind and water erosion risk in the watershed of the Ningxia-Inner Mongolia Reach of the Yellow River, China. Ecological Indicators 67, 117–131.

ECAGRC, E.C.o.A.o.G.R.o.C., 1993. Atlas of grassland resources of China (1:1M). China Atlas, Beijing.

Fan, J.W., Shao, Q.Q., Liu, J.Y., Wang, J.B., Harris, W., Chen, Z.Q., Zhong, H.P., Xu, X.L., Liu, R.G., 2010. Assessment of effects of climate change and grazing activity on grassland yield in the Three Rivers Headwaters Region of Qinghai-Tibet Plateau, China. Environ. Monit. Assess. 170, 571–584.

Fan, J.W., Zhong, H.P., Harris, W., Yu, G.R., Wang, S.Q., Hu, Z.M., Yue, Y.Z., 2008. Carbon storage in the grasslands of China based on field measurements of above- and below-ground biomass. Clim. Change 86, 375–396.

Fan, J., Harris, W., Zhong, H., 2016. Stoichiometry of leaf nitrogen and phosphorus of grasslands of the Inner Mongolian and Qinghai-Tibet Plateaus in relation to climatic

variables and vegetation organization levels. Ecological Res. 31, 821–829.
Field, C.B., 1998. Primary production of the biosphere: integrating terrestrial and oceanic components. Science 281, 237–240.
Fryrear, D., Saleh, A., Bilbro, J., Schomberg, H., Stout, J., Zobeck, T., 1998. Revised wind erosion equation (RWEQ). Wind erosion and water conservation research unit, USDA-ARS, Southern Plains area cropping systems research laboratory. Tech. Bullet. 1.
Fryrear, D.W., Krammes, C.A., Williamson, D.L., Zobeck, T.M., 1994. Computing the wind erodible fraction of soils. J. Soil Water Conserv. 49, 183–188.
Garg, A., Li, J., Hou, J., Berretta, C., Garg, A., 2017. A new computational approach for estimation of wilting point for green infrastructure. Measurement 111, 351–358.
Gill, R.A., Kelly, R.H., Parton, W.J., Day, K.A., Jackson, R.B., Morgan, J.A., Scurlock, J.M.O., Tieszen, L.L., Castle, J.V., Ojima, D.S., 2002. Using simple environmental variables to estimate below-ground productivity in grasslands. Global Ecol. Biogeography 11, 79–86.
Gong, G., Liu, J., Shao, Q., Zhai, J., 2014. Sand-Fixing Function under the Change of Vegetation Coverage in a Wind Erosion Area in Northern China. J. Resourc. Ecol. 5 (2), 105–114.
Gongbuzeren, Li, Li, Y., Li, W., 2015. China's rangeland management policy debates: what have we learned? Rangeland Ecol. Manage. 68, 305–314.
Gu, Y., Li, W., 2013. Research on the "Grazing Ban" Policy's Effect to Grassland Quality: analysis on the Scale of Herdsman Households. Acta Scientiarum Naturalium Universitatis Pekinensis 49, 288–296.
Han, D., Wang, G., Xue, B., Liu, T., Yinglan, A., Xu, X., 2018. Evaluation of semiarid grassland degradation in North China from multiple perspectives. Ecological Eng. 112, 41–50.
Harris, R.B., 2010. Rangeland degradation on the Qinghai-Tibetan plateau: a review of the evidence of its magnitude and causes. J. Arid Environ. 74, 1–12.
Hazra, B., Gadi, V., Garg, A., Ng, C.W.W., Das, G.K., 2017. Probabilistic analysis of suction in homogeneously vegetated soils. Catena 149, 394–401.
He, S.U., Liu, G., He, T., 2005. Reclamation of grassland and its harm. Grassland China 27, 61–63.
Ho, P., 2009. The clash over state and collective property: the making of the rangeland law. China Quarter. 161, 240.
Huang, L., Cao, W., Wu, D., Gong, G., 2016. The temporal and spatial variations of ecological services in the tibet plateau. J. Nat. Resourc. 31, 543–555.
Huang, L., Xiao, T., Zhao, Z., Sun, C., Liu, J., Shao, Q., Fan, J., Wang, J., 2013. Effects of grassland restoration programs on ecosystems in arid and semiarid China. J. Environ. Manage. 117, 268–275.
Ivits, E., Cherlet, M., Sommer, S., Mehl, W., 2013. Addressing the complexity in non-linear evolution of vegetation phenological change with time-series of remote sensing images. Ecological Indicat. 26, 49–60.
Jiang, G., Han, X., Wu, J., 2006. Restoration and management of the inner mongolia grassland require a sustainable strategy. Royal Swedish Acad. Sci. 35, 269–270.
Jiang, C., Li, D., Wang, D., Zhang, L., 2016a. Quantification and assessment of changes in ecosystem service in the Three-River Headwaters Region, China as a result of climate variability and land cover change. Ecological Indicat. 66, 199–211.
Jiang, C., Zhang, L., 2016. Ecosystem change assessment in the Three-river Headwater Region, China: Patterns, causes, and implications. Ecological Eng. 93, 24–36.
Jiang, L., Xiao, Y., Zheng, H., Ouyang, Z., 2016b. Spatio-temporal variation of wind erosion in Inner Mongolia of China between 2001 and 2010. Chinese Geographical Sci. 26, 155–164.
John, R., Chen, J., Ou-Yang, Z.-T., Xiao, J., Becker, R., Samanta, A., Ganguly, S., Yuan, W., Batkhishig, O., 2013. Vegetation response to extreme climate events on the Mongolian Plateau from 2000 to 2010. Environ. Res. Lett. 8, 035033.
Kawanabe, S., Nan, Y., Oshida, T., Kou, Z., Jiang, D., Takada-Oikawa, N., Mukaiyama, S.I., 1998. Degradation of Grassland in Keerqin Sandland, Inner Mongolia, China. J. Jpn. Soc. Grassland Sci. 44, 109–114.
Kuang, W., Chen, L., Liu, J., Xiang, W., Chi, W., Lu, D., Yang, T., Pan, T., Liu, A., 2016. Remote sensing-based artificial surface cover classification in Asia and spatial pattern analysis. Sci. China Earth Sci. 59, 1720–1737.
Liao, G., Jia, Y., 1996. Rangeland Resources of China. Science and Technology of China Press.
Li, W., Huntsinger, L., 2011. China's grassland contract policy and its impacts on herder ability to benefit in inner mongolia: tragic feedbacks. Ecol. Soc. 16.
Liu, B.Y., Nearing, M.A., Shi, P.J., Jia, Z.W., 2000. Slope length effects on soil loss for steep slopes. Soil Sci. Soc. Am. J. 64, 1759–1763.
Liu, S., Zamanian, K., Schleuss, P.-M., Zarebanadkouki, M., Kuzyakov, Y., 2018. Degradation of Tibetan grasslands: consequences for carbon and nutrient cycles. Agric., Ecosyst. Environ. 252, 93–104.
Liu, J., Liu, M., Tian, H., Zhuang, D., Zhang, Z., Zhang, W., Tang, X., Deng, X., 2005. Spatial and temporal patterns of China's cropland during 1990–2000: an analysis based on Landsat TM data. Remote Sens. Environ. 98, 442–456.
Liu, J., Kuang, W., Zhang, Z., Xu, X., Qin, Y., Ning, J., Zhou, W., Zhang, S., Li, R., Yan, C., Wu, S., Shi, X., Jiang, N., Yu, D., Pan, X., Chi, W., 2014. Spatiotemporal characteristics, patterns, and causes of land-use changes in China since the late 1980s. J. Geographical Sci. 24, 195–210.
Liu, J., Shao, Q., Yu, X., Huang, H., 2016. Comprehensive Monitoring and Evaluation of Land Ecosystem in China. Science Press.
Liu, Y., 2015. The national monitoring report of grassland of China in 2014. China Animal Industry 18–31.
Lobell, D.B., Hicke, J.A., Asner, G.P., Field, C.B., Tucker, C.J., Los, S.O., 2002. Satellite estimates of productivity and light use efficiency in United States agriculture, 1982–98. Global Change Biol. 8, 722–735.
Lü, Y., Fu, B., Feng, X., Zeng, Y., Liu, Y., Chang, R., Sun, G., Wu, B., 2012. A policy-driven large scale ecological restoration: quantifying ecosystem services changes in the Loess Plateau of China. PLos One 7, e31782.
Ma, M., Frank, V., 2006. Interannual variability of vegetation cover in the Chinese Heihe river basin and its relation to meteorological parameters. Int. J. Remote Sens. 27, 3473–3486.
McCool, D.K., Brown, L.C., Foster, G.R., Mutchler, C.K., Meyer, L.D., 1987. Revised slope steepness factor for the universal soil loss equation. Trans. ASAE – Am. Soc. Agric. Engineers (USA) 30, 1387–1396.
Millennium Ecosystem Assessment, 2005. Ecosystems and Human Well-being: Synthesis.
Ouyang, Z., Zhang, L., Wu, B., Li, X., Xu, W., Xiao, Y., Zheng, H., 2015. An ecosystem classification system based on remote sensor information in China. Acta Ecologica Sinica 35, 219–226.
Ouyang, Z., Zheng, H., Xiao, Y., Polasky, S., Liu, J., Xu, W., Wang, Q., Zhang, L., Xiao, Y., Rao, E., 2016. Improvements in ecosystem services from investments in natural capital. Science 352, 1455–1459.
Renard, K.G., Foster, G.R., Weesies, G.A., McCool, D.K., Yoder, D.C., 1997. Predicting soil erosion by water: a guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE). Agriculture Handbook.
Ren, Y., Lü, Y., Fu, B., 2016. Quantifying the impacts of grassland restoration on biodiversity and ecosystem services in China: a meta-analysis. Ecological Eng. 95, 542–550.
Shao, Q., Cao, W., Fan, J., Huang, L., Xu, X., 2016. Effects of an ecological conservation and restoration project in the Three-River Source Region, China. J. Geographical Sci. 27, 183–204.
Wang, J., Dong, J., Liu, J., Huang, M., Li, G., Running, S., Smith, W., Harris, W., Saigusa, N., Kondo, H., Liu, Y., Hirano, T., Xiao, X., 2014. Comparison of Gross Primary Productivity Derived from GIMMS NDVI3g, GIMMS, and MODIS in Southeast Asia. Remote Sens. 6, 2108–2133.
Wang, J., Dong, J., Wang, S., Zhang, L., He, H., Yi, Y., Lu, G., Oyler, J., Smith, W.K., Zhao, M., 2017a. Decreasing net primary production due to drought and slight decreases in solar radiation in China from 2000 to 2012. J. Geophys. Res. Biogeosci.
Wang, X., 2009. Pastoral Communities under Environmental Pressure. Social Sciences Academic Press.
Wang, X., Chen, F., Dong, Z., 2006. The relative role of climatic and human factors in desertification in semiarid China. Global Environ. Change 16, 48–57.
Wang, Z., Deng, X., Song, W., Li, Z., Chen, J., 2017b. What is the main cause of grassland degradation? A case study of grassland ecosystem service in the middle-south Inner Mongolia. Catena 150, 100–107.
Wu, R., Tiessen, H., 2002. Effect of land use on soil degradation in alpine grassland soil, China. Soil Sci. Soc. Am. J. 66, 1648–1655.
Wu, Z., Wu, J., Liu, J., He, B., Lei, T., Wang, Q., 2013. Increasing terrestrial vegetation activity of ecological restoration program in the Beijing-Tianjin Sand Source Region of China. Ecological Eng. 52, 37–50.
Xing, Q., Liu, A., Liu, Y., Gao, W., 2005. Study on change rangeland vegetation, change using MODIS-NDVI in Xilinguole grassland. Acta Agrestia Sinica 15–19.
Xu, B., Yang, X., Tao, W., Qin, Z., Liu, H., Miu, J., 2007. Remote Sensing monitorning upon the grass production in China. Acta Ecologica Sinica 405–413.
Yang, Y., Wang, Z., Li, J., Gang, C., Zhang, Y., Zhang, Y., Odeh, I., Qi, J., 2016. Comparative assessment of grassland degradation dynamics in response to climate variation and human activities in China, Mongolia, Pakistan and Uzbekistan from 2000 to 2013. J. Arid Environ. 135, 164–172.
Yu, C., Zhang, Y., Claus, H., Zeng, R., Zhang, X., Wang, J., 2012. Ecological and environmental issues faced by a developing Tibet. Environ. Sci. Technol. 46, 1979–1980.
Yu, G., Lu, C., Xie, G., 2005. Progress in ecosystem services of grassland. Resourc. Sci. 27, 172–179.
Zhang, H., Fan, J., Shao, Q., Zhang, Y., 2016. Ecosystem dynamics in the 'Returning Rangeland to Grassland' programs, China. Acta Prataculturae Sinica 25, 1–15.
Zhang, W., Xie, Y., Liu, B., 2002. Rainfall Erosivity Estimation Using Daily Rainfall Amounts. Scientia Geographica Sinica 22, 705–711.
Zhang, Z., Wang, X., Zhao, X., Liu, B., Yi, L., Zuo, L., Wen, Q., Liu, F., Xu, J., Hu, S., 2014. A 2010 update of National Land Use/Cover Database of China at 1:100000 scale using medium spatial resolution satellite images. Remote Sens. Environ. 149, 142–154.
Zhao, T., Ou, Y., Jia, L., Zheng, H., 2004. Ecosystem services and their valuation of China grassland. Acta Ecologica Sinica 24, 1101–1110.
Zhou, H., Zhao, X., Tang, Y., Gu, S., Zhou, L., 2005. Alpine grassland degradation and its control in the source region of the Yangtze and Yellow Rivers, China. Grassland Sci. 51, 191–203.
Zhou, L., Zhu, H., Zhong, H., Yang, H., 2016. Spatial analysis of the soil total carbon in Ili, Xinjiang Uygur Autonomous Region, China. Pratacultural Sci. 33, 1963–1974.
Zobeck, T.M., 1991. Abrasion of crusted soils: influence of abrader flux and soil properties. Soil Sci. Soc. Am. J. 55, 1091–1097.